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## A STUDY OF LOW LEVEL AIR TRAJECTORIES AT OAK RIDGE, TENN.\*

FRANK GIFFORD, JR.

U. S. Weather Bureau, Washington, D. C.

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### ABSTRACT

Approximately 2,000 zero-lift, double-theodolite pilot balloon observations made at Oak Ridge, Tenn., are analyzed in order to study low level air trajectories over hilly terrain. Paths of air parcels are found to fall into characteristic groups, depending on wind speed and stability conditions. Eddy patterns for these groups are determined, and these are found to resemble similar patterns determined for different types of terrain. The properties of low level air flow, particularly of vertical velocity patterns, are displayed in various ways. Slope winds due to thermal-dynamical effects appear to contribute more to these patterns than does a purely mechanical lifting effect.

### INTRODUCTION

This report summarizes the main results of a study of low level air trajectories observed at Oak Ridge, Tenn. A Weather Bureau meteorological group assigned there at the request of the Atomic Energy Commission to study the micrometeorology of the area, made almost a thousand neutral, or zero-lift, pilot balloon observations between January 1949 and February 1950, as part of an intensive program of observations. This unique body of data will be analyzed for what light it can throw on local air flow patterns over the hilly terrain at Oak Ridge, as well as on the character of low level turbulence in general.

The use of neutral pilot balloons for such a purpose is not new. Lange's studies, in connection with the Rhön-Rossitten glider society, [3, 4, 5], are probably the best known example. Other interesting studies have been made, particularly by Höhndorf and Müller [2], and by Nitze [9]. The principal object of Lange's work was the determination of vertical velocities associated with lee eddies which he observed to form to the leeward of dunes, hills, or coastal cliffs, then to detach themselves and travel downwind. These studies are characterized by meticulous attention to observational techniques and sources of error and a thorough analysis of results, using

the detailed case-study approach. Certain properties of low level air trajectories (such as vertical velocity patterns) were recorded for the first time, and then were observed to be reproduced, qualitatively, under similar meteorological conditions. Forty ground and 41 air releases are reported in Lange's work, all daytime and made mostly during the midafternoon. The present study deals with a far larger body of data. This permits several new types of analysis and yields correspondingly more complete information, while substantially verifying the earlier results, where these apply.

### LOCALE AND TECHNIQUE OF THE OBSERVATIONS

The town of Oak Ridge is located in eastern Tennessee in the broad northeast-southwest valley lying between the Cumberland Mountains and the Great Smokies. The Smokies rise to over 5,000 feet about 40 miles east-south-east of Oak Ridge, and the Cumberland Plateau reaches a general elevation of 2,000 feet some 20 miles to the west-northwest. In between, and running parallel to the main valley, are a number of smaller ridges and valleys of which Blackoak Ridge, from which the town gets its name, is one. The valley floors near Oak Ridge are at nearly 800 feet above sea level, and the ridges rise from 300 to 500 feet above that. Drainage in the valleys is to the southwest into the Clinch River. The land consists of wooded ridges and mainly cleared valleys. Figure 1 is a topo-

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FIGURE 1.—Topographical map of the Oak Ridge area. Numbered dots indicate locations of stations continuously recording wind, temperature, humidity, and rainfall.

graphical map showing the area for several miles around the balloon release point, which was a platform 30 feet high near the middle of Bethel Valley, approximately 8 miles south-southwest of the town of Oak Ridge.

The technique of neutral pibals is quite simple [10]. An ordinary balloon, in this case a 10-gram ceiling ballon, is inflated until its free-lift is just zero. It is released and then followed with two theodolites. In the present experiment a baseline of about 800 feet, running across the valley, was used, and readings were made at intervals of 30 seconds. The diameter of the balloons averaged about 10 inches. Neutral runs were made successively during two 45-minute periods each day starting at 1100 and 2300 LST, weather and personnel permitting. A balloon was released, followed until it was lost, and then a new release was made. In this way, groups of from 1 or 2 to as many as 6 runs were obtained. Azimuth and elevation angles were recorded on punched cards, and the balloon's distance and height, direction and magnitude of the velocity vector, vertical velocity component, and horizontal distance components were calculated by punched-card machine. With a 30-second reading interval, about 25,000 observations were obtained during the course of the experiment. For a particular run only those observations involving horizontal distances from the release point of less than 10,000 feet are considered in this study. This reduced the total number of individual observations to about 18,000. The length of the baseline was such that the calculations for greater distances were not sufficiently reliable.

There are certain limitations and sources of error peculiar to neutral pilot balloon observations. The slight pressure excess causes diffusion through the balloon's wall; radiational heating or cooling of the balloon occurs; if the vertical temperature gradient is not adiabatic, buoyancy forces arise. All these affect the free lift. Such sources of error were studied theoretically in detail by Lange [3], who concluded that the possible free lift which might occur is not excessively large, and that the balloons remain reasonably balanced. A second kind of error arises in a continued experiment such as the present one because of the difficulty of weighing off the balloons in an exactly balanced condition in all kinds of weather. To the extent that this sort of error is random, it will tend to be minimized when large numbers of observations are considered.

#### SUPPLEMENTARY METEOROLOGICAL INFORMATION

In addition to the usual meteorological information, a wide variety of supplementary material was available at Oak Ridge for comparison with the neutral data. A network of stations continuously recording wind, temperature, humidity, and rainfall was in operation. These stations were located at the numbered dots on figure 1, and they give a detailed meteorological coverage of the area. Winds and temperature measurements at several heights up to 210 feet were available at the neutral release point. Detailed single theodolite pilot balloon runs were

made just before and just after each neutral period. For the portion of the neutral experiment from June 1949 on, frequent temperature soundings by captive blimp were available [7]. A summarization of the essential features of much of these data, including wind speed, shear, and stability measures, was available for each hour in the form of a 10-digit classification code, and this information was punched into the neutral card deck.

#### THE NEUTRAL TYPES

As a starting point in the analysis, a number of neutral trajectories, position plots in  $x$ - $y$  and  $x$ - $z$  coordinates, were drawn. One hundred observing periods, or about 250 individual runs were examined. It soon became clear that these could be grouped qualitatively into four classes according to the appearance of the  $x$ - $z$  trajectory, the plot of distance against height of a group of runs. The general appearance of each of these is shown, schematically, in figure 2. Type A, a daytime, light wind type associated with unstable lapse rates in the lowest few hundred feet, appears to be the result of convective heating. Balloons are carried upward rapidly and do not travel much horizontally before being carried back down to near the ground. Some balloons have been observed to go up into cumulus clouds during this type of run. Type B also occurs during the daytime, but is associated with stronger winds and often with more cloudiness and less instability than is Type A. Type C occurs at night, with moderate to strong winds. The balloons go out in steady paths, two or more often being virtually superimposed. The fourth type, D, is associated with stable conditions and light surface winds at night. The balloons slowly rise, then drift slowly back down, often without moving very far out.

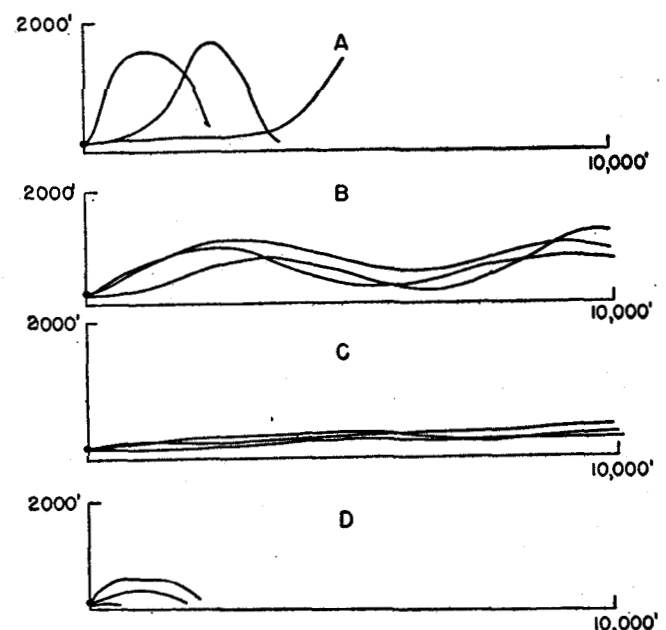


FIGURE 2.—Schematic distance—height trajectories illustrating the four basic neutral balloon run types.

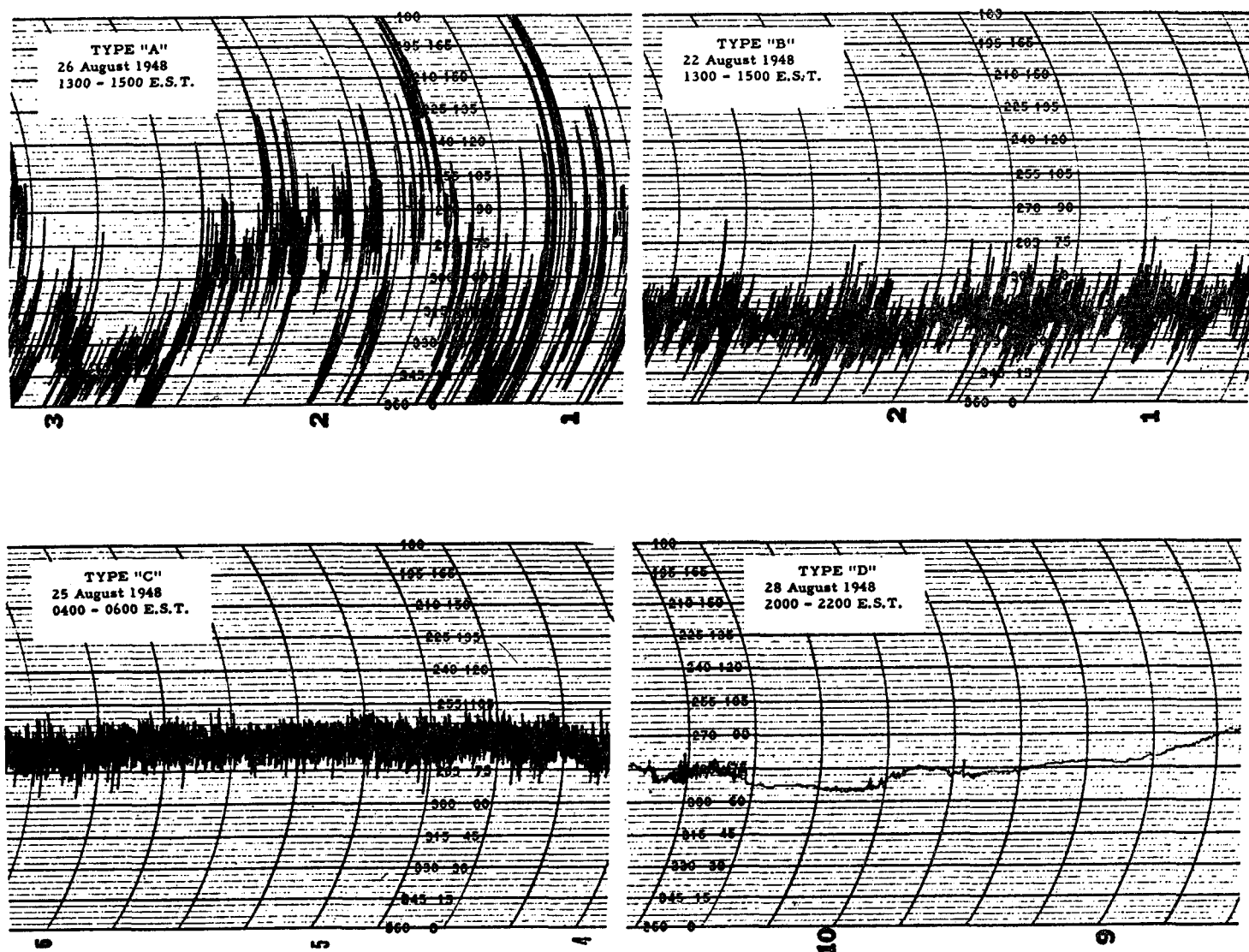


FIGURE 3.—Wind direction traces illustrating the Brookhaven turbulence types [6].

This system of classification will be recognized as directly paralleling one suggested by the meteorology group at Brookhaven National Laboratories [6] as a means of classifying the type of turbulence, using the trace of a continuous recording wind vane high on their tower. Reference is also made to a similar classification by Giblett [1]. Figure 3 shows the Brookhaven scheme. Their type A is characterized by highly irregular, short period fluctuations superimposed on an irregular, longer period swinging of the vane. Type B has similar short period motion together with a steadier long period oscillation of smaller amplitude than the A-type has. Type C is characterized by rapid, short period oscillations only, and Type D shows hardly any motion of the vane. The Brookhaven types are associated with wind speed and stability in the same sense as the neutral types are.

It is evident, comparing figures 2 and 3, that the neutral observations completely filter out the short period oscillations of types B and C. Continuous wind direction

traces at a height of 210 feet were available for 30 of the neutral periods comprising 54 individual runs. These were classified according to the Brookhaven typing system and the result compared with the corresponding neutral types. Over 90 percent agreement was found. This result fits the neutral observations into the general picture of low level turbulent flow as it is already understood. Furthermore, it is possible in the light of these observations, to infer from a wind-direction trace what sort of paths the air parcels are following.

Because it separates what appear to be essentially different patterns of flow, or turbulence regimes, this classification scheme has been used as a basis for the remainder of the analysis.

#### SOME TYPICAL NEUTRAL RUNS

From the many plotted runs, two sets representative of each turbulence type are presented in this section.

Figure 4 shows typical A-groups. Panel (a) contains

distance vs. height and distance vs. azimuth plots of a group of three consecutive runs made on a clear August day. There was a flat High centered just east of the Oak Ridge area, near Bristol, Tenn., giving light easterly winds aloft. The micronet stations (fig. 1) in valley locations (001, 003, 004) followed the general circulation with light, northeasterly winds, whereas the slope stations (005, 010, 012) showed evidence of upslope winds. The lapse rate was strongly superadiabatic below 200 feet but more stable above. Dots and crosses give the balloon's position at the end of each 30-second interval, so that the distance between them is proportional to wind speed. All these balloons show a good deal of vertical motion, the maximum vertical velocities being about  $\pm 4$  mph. Panel (b) shows a second A-group. The principal features of the first group are repeated.

Two typical B-groups are shown in figure 5. The first group of runs, panel (a) was made on a clear December day. A ridge of high pressure extended north-south over the eastern part of the country, causing a somewhat stronger easterly flow than in the first A-case. Valley and ridge micronet stations showed northeasterly winds, with slight upslope components at the slope stations. The balloons followed a wavelike path in the vertical with peaks about every 2,000 feet at first. The maximum height the balloons reached is only about 1,000 feet. The second B-group, panel (b) of figure 5, was made on a clear November day with moderate westerly flow over the area. The undulation here has a length of around 4,000 feet.

Figure 6 shows two C groups. In the first, panel (a), the balloons are responding to a strong southwesterly gradient associated with a trough through the central United States. The sky was overcast, base 2,000 feet, and there was intermittent rain in the area, preceding a polar outbreak in January. Micronet winds were mainly southerly, following the general circulation. The balloons follow nearly identical paths, displaced from one another slightly more horizontally than vertically. They cross Chestnut Ridge at about 5,000 and Pine Ridge at about 10,000 feet out, but any topographic effect is evidently slight. The second C-group (panel (b)), made on a partly cloudy November night when the area was being affected by a moderate northwesterly flow due to a High over the Plains States, duplicates the appearance of the first, except that there is even more disparity between horizontal and vertical dispersion of the balloons.

Figure 7 shows two D-groups. The first, panel (a), was made on a partly cloudy February night with a High centered near Oak Ridge. Valley micronet winds were calm, and ridgetop winds light, westerly. Two of the balloons rose slowly, traveled out a short distance, and sank. The third became imbedded in the stronger flow aloft, above the ground inversion, and was carried away more rapidly, much as a C-type. The second D-group was made on a June night with an indefinite trough giving a weak, southerly flow over the area. The balloons rose

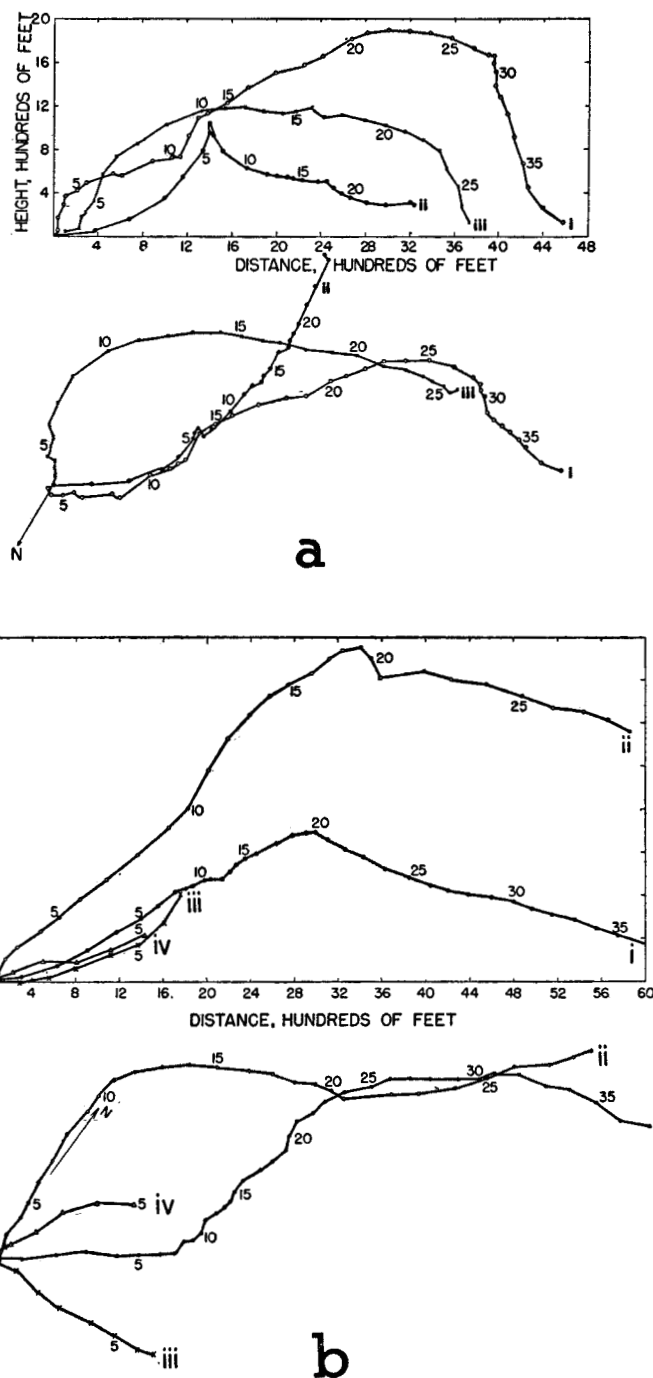


FIGURE 4.—Trajectories in the vertical and horizontal planes of two typical A-groups of neutral balloon observations.

slightly, drifted slowly across the valley, and sank to the ground near the southeastern slope, apparently following a local drainage circulation.

These are all typical neutral runs. Most groups of neutrals fall readily into 1 of the 4 types, although there are many interesting peculiarities. Of the 100 groups which were actually plotted and examined, about 250 individual runs, only 1 or 2 were out-and-out misfits, defying classification.

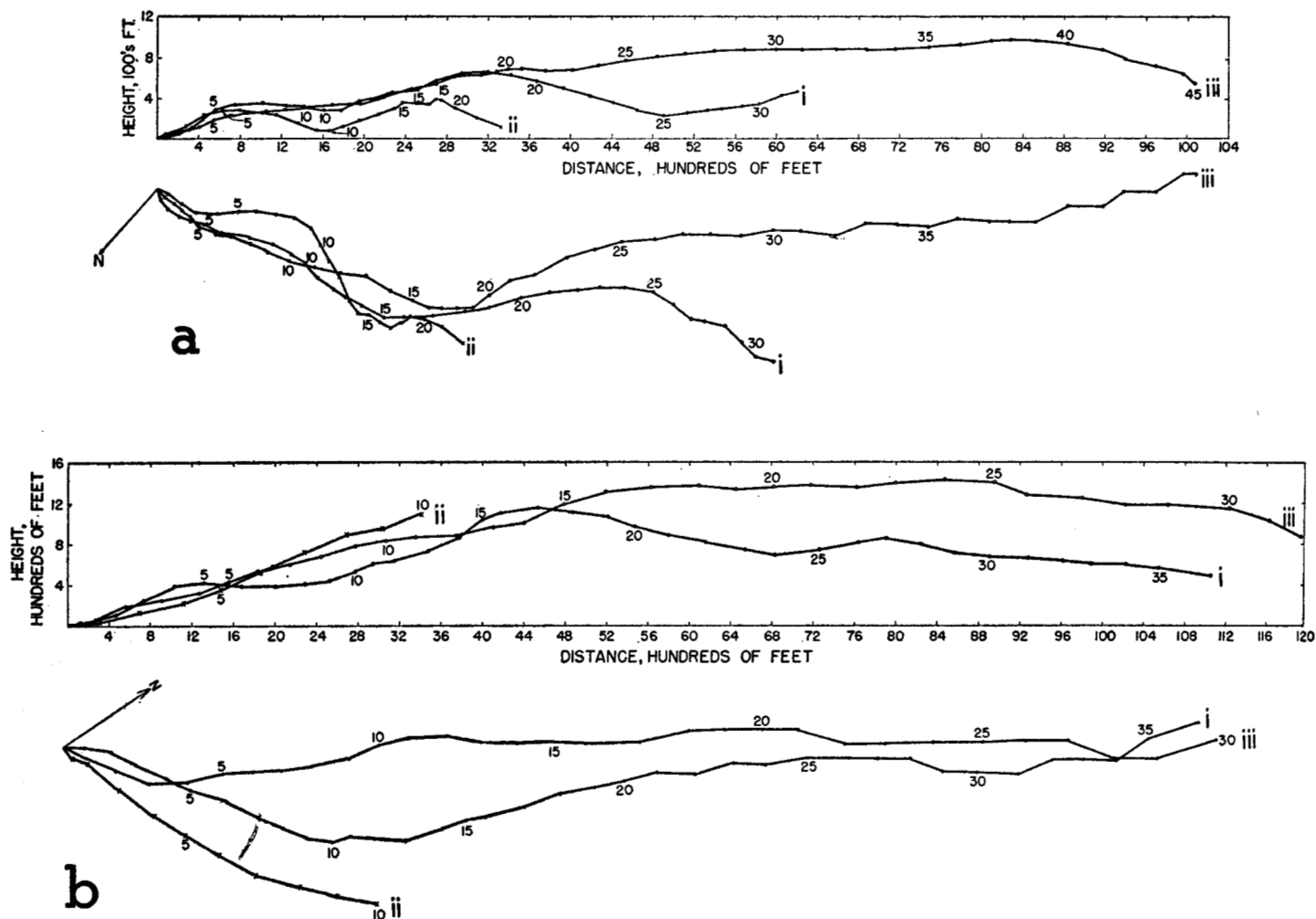


FIGURE 5.—Trajectories in the vertical and horizontal planes of two typical B-groups of neutral balloon observations.

### EDDY PATTERNS

When the mean horizontal velocity vector determined by a neutral balloon run is subtracted from the  $x$ - $y$  and  $x$ - $z$  plots such as have been examined above, characteristic patterns result. These are, essentially, what the neutral runs would look like to an observer moving along with a steady velocity equal to the mean of the run. A selection of such eddy patterns for each of the turbulence types is presented in figure 8.

The A types correspond to the trajectories of figure 4. The eddies are elongated in the vertical and transverse directions, and have dimensions of around 1,000 to 2,000 feet. It is a very interesting feature of this particular group that the sense of rotation of the center run, in both the horizontal and vertical patterns, is opposite to that of the two others. The end balloons, runs i and iii, rose with a velocity deficit and went to the left of the main stream, then picked up speed and returned to the right while lowering. Run ii, in contrast, rose with an excess velocity, actually faster than the mean for the run, and went to the right, ultimately slowing down and lowering. These

patterns indicate air motion in the form of counter-rotating horizontal helical vortices, a form suggested by Woodcock and Wyman [11] to explain their observations of a banded appearance of the sea surface under similar weather conditions, but which they were unable, at that time, to observe directly.

The panel of figure 8 labeled Type B shows eddy patterns due to the B-types. The B eddies are smaller than the A's, just as were the waves in the trajectory plot. Once again, the sense of rotation of the second eddy is reversed. Some small loops, about 100 to 200 feet in diameter, are evident.

These patterns, both A- and B-types, are comparable in dimension, appearance, and sense of the rotation with similar ones found by Lange. Except that no lee eddies, such as Lange occasionally observed ([3], p. 22, fig. 21, turbulence element #52) were found, the resemblance between the Oak Ridge patterns and those Lange found over much different terrain types is very striking. Lange's observations were usually made either over rather flat terrain or in the area of some such bluff obstacle as a dune

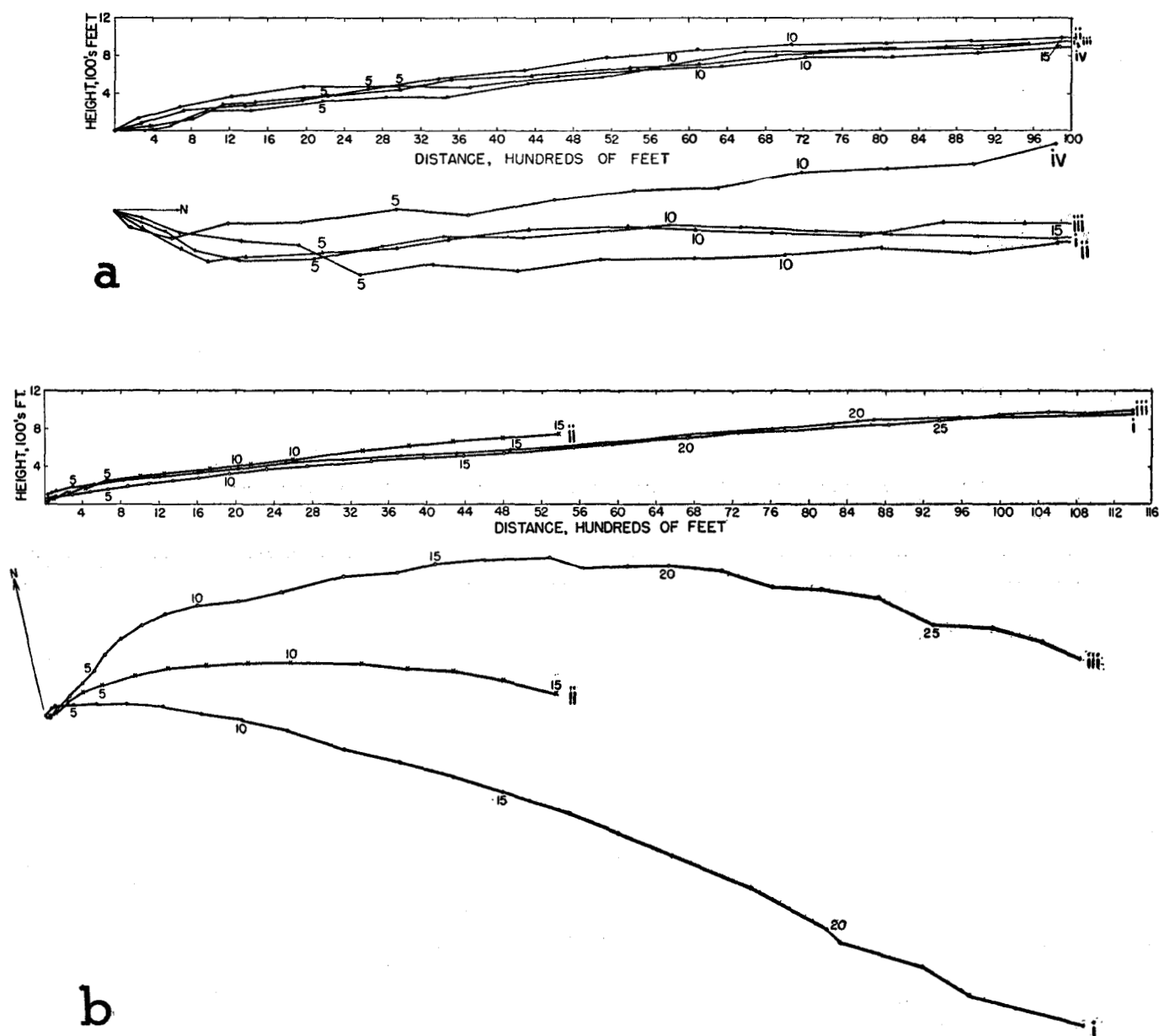


FIGURE 6.—Trajectories in the vertical and horizontal planes of two typical C-groups of neutral balloon observations.

or a cliff. The Oak Ridge observations, being made over low, comparatively gently sloping ridges, lie on a scale of terrain ruggedness somewhere in between. The similarity of eddy patterns of the A- and B-types to Lange's indicate that these particular eddies are characteristic properties of low level air flow and that their properties do not depend on the presence of large ground obstacles.

There is no true eddy pattern for type C, (fig. 8), either in the horizontal or in the vertical. The apparent half-rotation in the vertical plane is simply a depiction of the vertical velocity gradient. Of the D-type eddy patterns (fig. 8), the first two have a slow clockwise rotation, the pattern being this time elongated horizontally. The third run of this group looks like a C-type; the balloon in this

case penetrated the ground inversion and reached the faster moving air aloft.

It seems clear from these patterns, that the neutrals respond primarily to large eddies, probably thermal in origin, when these are present but show little indication of the small-scale mechanical turbulence which we know, from fixed wind measuring instruments, to exist. The size of these larger eddies is of the order of thousands of feet in the case of daytime thermals, and of hundreds for the sluggish, nighttime eddies. During the day, with light winds and instability, the eddies are elongated vertically, during the night horizontally. The nighttime eddies are of the proper size and character to be explained by slope and valley drainage circulations. The neutrals

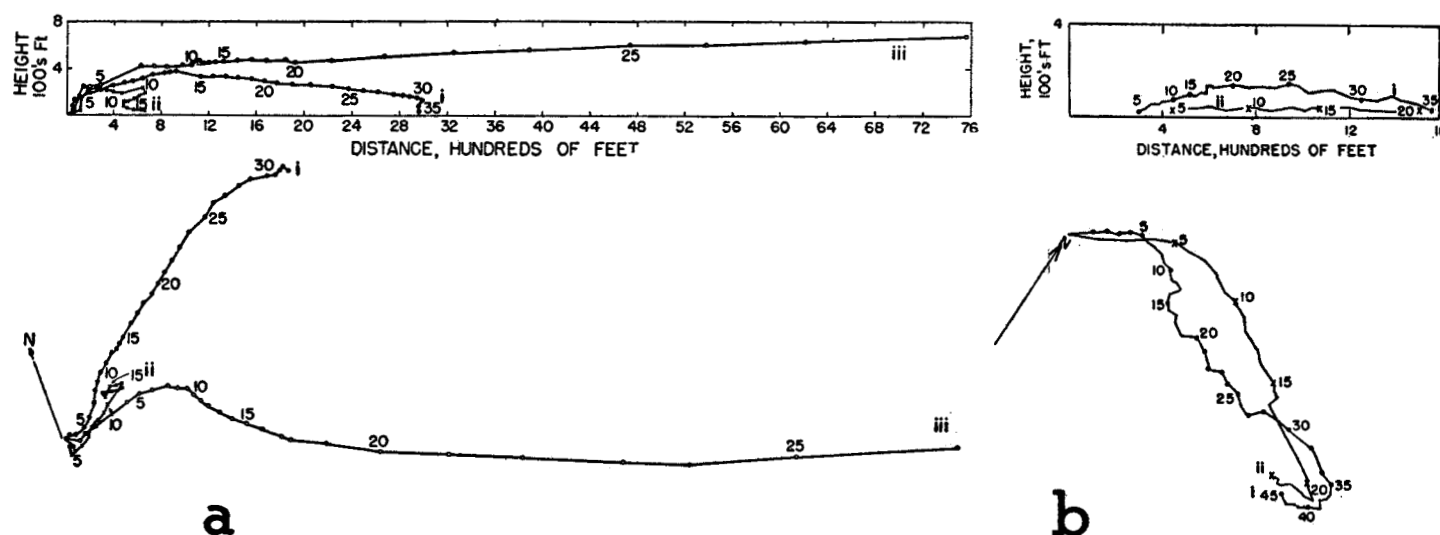


FIGURE 7.—Trajectories in the vertical and horizontal planes of two typical D-groups of neutral balloon observations.

give no direct indication of exactly what mechanisms operate to produce these eddies, but they are larger than the largest roughness obstacles, the ridges, in the case of the daytime eddies by an order of magnitude. Lee eddies were not found.

#### THE LAGRANGIAN CORRELATION COEFFICIENT

In the statistical theory of turbulence, two fundamental quantities are defined, the scale and the intensity of turbulence; and these concepts are basic in the development of such applications as the theory of turbulent diffusion. The scale is defined in terms of the Lagrangian correlation coefficient,  $R_t$ , the correlation between turbulence velocity fluctuations of a parcel measured at two different times. The scale of turbulence is the integral of this coefficient over all time intervals:

$$L = \int_0^{\infty} R_t d\xi$$

The intensity of turbulence is defined as the square root of the ratio of the turbulent energy to the mean energy:

$$I = \frac{\sqrt{\overline{v'^2}}}{\bar{u}}$$

But the mean velocity,  $\bar{u}$ , must be taken over a time interval long enough for  $R_t$  to attain zero in such a way that the integral has some value. Otherwise the intensity is not defined.

Data with which to determine  $R_t$  in the atmosphere are not common by any means because of the difficulty of making observations on a parcel of air. Neutral pilot balloons are among the few possible methods. For this reason, the curves exhibited in figure 9 should be of interest. These are  $R_t$  vs.  $\xi$  curves for a selection of neutral runs representing each type. The time interval involved is, in each case, less than ten minutes ( $\xi < 20$ ). At this

interval there is no clear indication that the correlation curve is tending toward zero, which would be required to give meaning to the expression for the scale of turbulence. It is possible that, if the experiment could have been carried on for a longer time, the values of  $R_t$  would have tended to zero. This suggests that special attention be given to those few runs whose duration was more than 30 minutes. Three such runs, each having durations in the neighborhood of 40 minutes, were accordingly studied from this standpoint. The correlation curves for these runs also failed to approach zero.

#### MEAN VERTICAL VELOCITY CROSS SECTIONS

The particular effects, if any, which low ridges might produce on the air flow of the lower few thousand feet (contrasted with the effect of the larger mountain-valley system) are three: lee eddies, slope winds caused by heating, and a purely topographic lifting of the air. In this connection the final problem considered is the distribution of vertical velocities over various parts of the neutral study.

Figure 10 shows the joint relation, for the 100 plotted neutral runs, between turbulence type, and measures of low level stability and 5,000-foot wind speed, these particular quantities being among those punched into each neutral IBM card. It is seen that light winds and instability correspond to the A-type, and so on. With considerable justification, a sort can be made on the stability and wind speed values indicated by the dashed lines in the figure, and the entire body of observations separated in this way by type. Notice that the A's and B's are well separated from the C's and D's by the isothermal, but that the separation between A's and B's and between C's and D's is considerably poorer.

Figure 11, showing isopleths of vertical velocity, was obtained by sorting first on turbulence type and then selecting all observations with azimuths in a  $10^\circ$  arc up

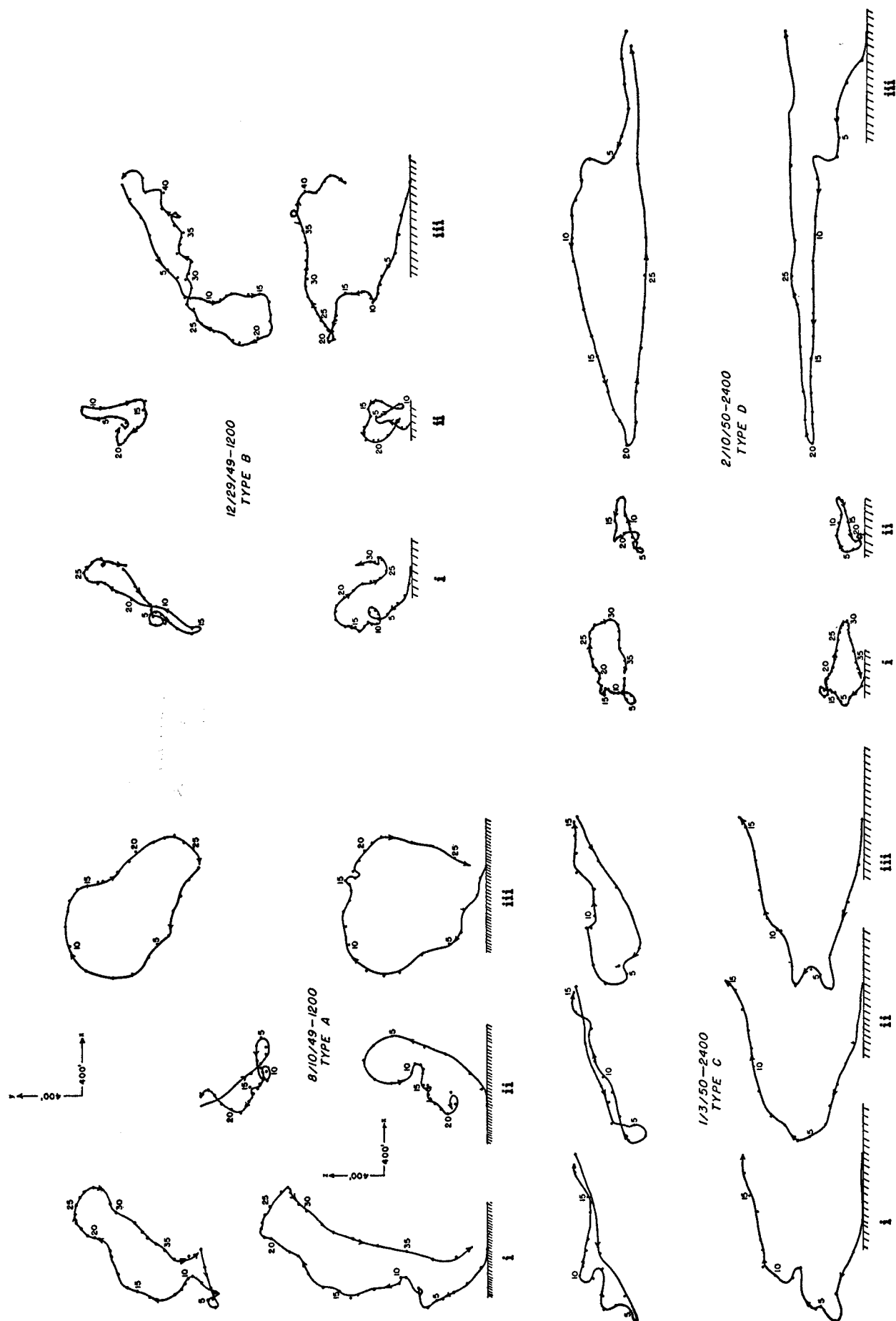


FIGURE 8.—Eddy patterns; horizontal (x-y) and vertical (x-z) plots of neutral trajectories from which the mean horizontal wind velocity vectors have been subtracted.

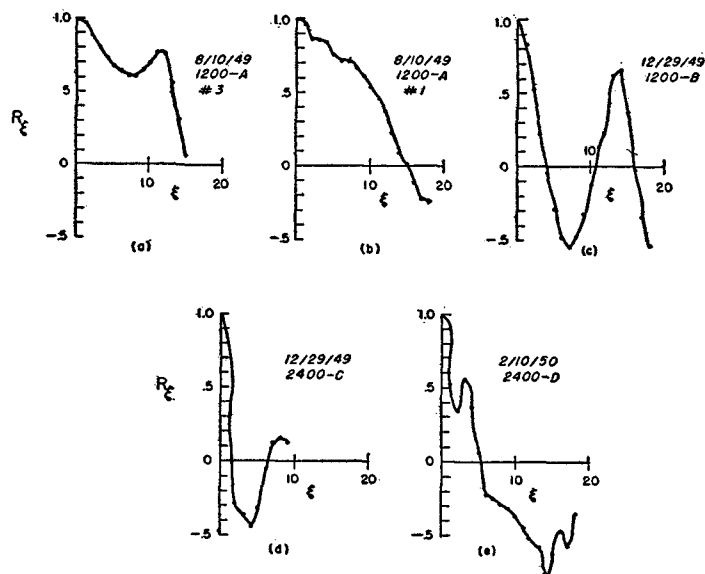


FIGURE 9.—Lagrangian autocorrelation function for typical neutral balloon runs.

and down Bethel Valley and in another arc across the ridges at a right angle to the valley. Observations of vertical velocity in these directions and for 500-foot height intervals were averaged and these cross-sections resulted. Of the four panels, those for the A-type present the most interesting patterns. The extent and intensity of regions of upward and downward motions are about the same for cross-valley as for up-and-down valley flow, and there is no clear indication of a purely mechanical lifting effect of the ridge. The plots for Type A, instead, show the broad areas of upward and downward moving currents which it is customary to associate with thermal activity. An interesting point arises. These are mean pictures, and even when averaged over a large number of observations the mean vertical velocity is not zero. Naturally, it is not known whether the same patterns of mean vertical velocity would have resulted if the balloons had been released at some other point, say near an area which now appears as a center of negative vertical velocity. At least near the release point it is evident why vertical velocities must appear to be positive, on the average. Otherwise the balloons would be carried to the ground and would never leave the immediate area. It doesn't seem likely that this process of natural selection could influence the averages for any great distance from the release point, and it seems necessary to conclude that the patterns do represent some real organization of the motion. Whether this is a terrain effect is problematical.

It appears that the main influence of the low ridges on the air flow at levels up to 2,000 or 3,000 feet is to produce thermal-type circulations. The vertical velocity cross sections have not clearly shown any purely topographical effect of the ridges on vertical velocities except in the

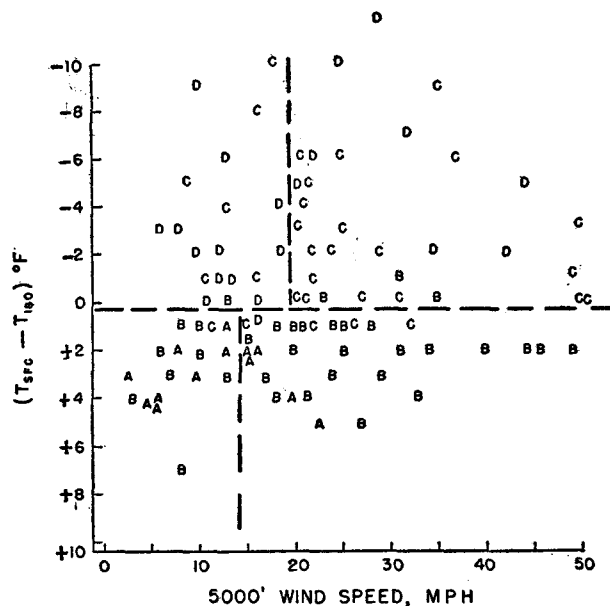


FIGURE 10.—Turbulence type plotted as a joint function of low level thermal stability (surface temperature minus 180-foot temperature) and of 5,000-foot wind speed for 100 neutral balloon runs.

case of the initial upslope lifting of the balloons under strong, cross-valley wind conditions (type C, 320°–329°). If present, such effects are largely obscured by the larger eddies.

#### VERTICAL VELOCITY FREQUENCY DISTRIBUTION

Figures 12 and 13 show frequency distributions of vertical velocities over various types of terrain. The 10,000-foot circle within which the neutral observations are considered was divided into 10° azimuth sectors and 1,000-foot distance intervals. Each of these little areas was then classified according to whether the terrain in it was primarily valley, upslope, crest, downslope, or irregular (relative to a line radiating from the balloon release point). This information was punched into the card deck and the frequency distributions appearing in the figure were obtained. The separation of azimuths 50° through 229° (fig. 12) from azimuths 230° through 49° (fig. 13) is for the purpose of distinguishing north-facing from south-facing slopes.

The most prominent feature of these distributions is, once again, the pronounced effect of lapse rate. The C- and D-types have much more peaked distributions than do the A- and B-types, indicating the strong damping effect on vertical motions which is associated with stability. The little arrows below the abscissa of each frequency distribution, in figures 12 and 13, mark the 12.5 and 50th percentile points and give, according to how close together they are, a rough measure of the standard deviations of these distributions. There are other interesting points. Most of the distributions are skewed to the left of zero vertical velocity. In other words, upward velocities are

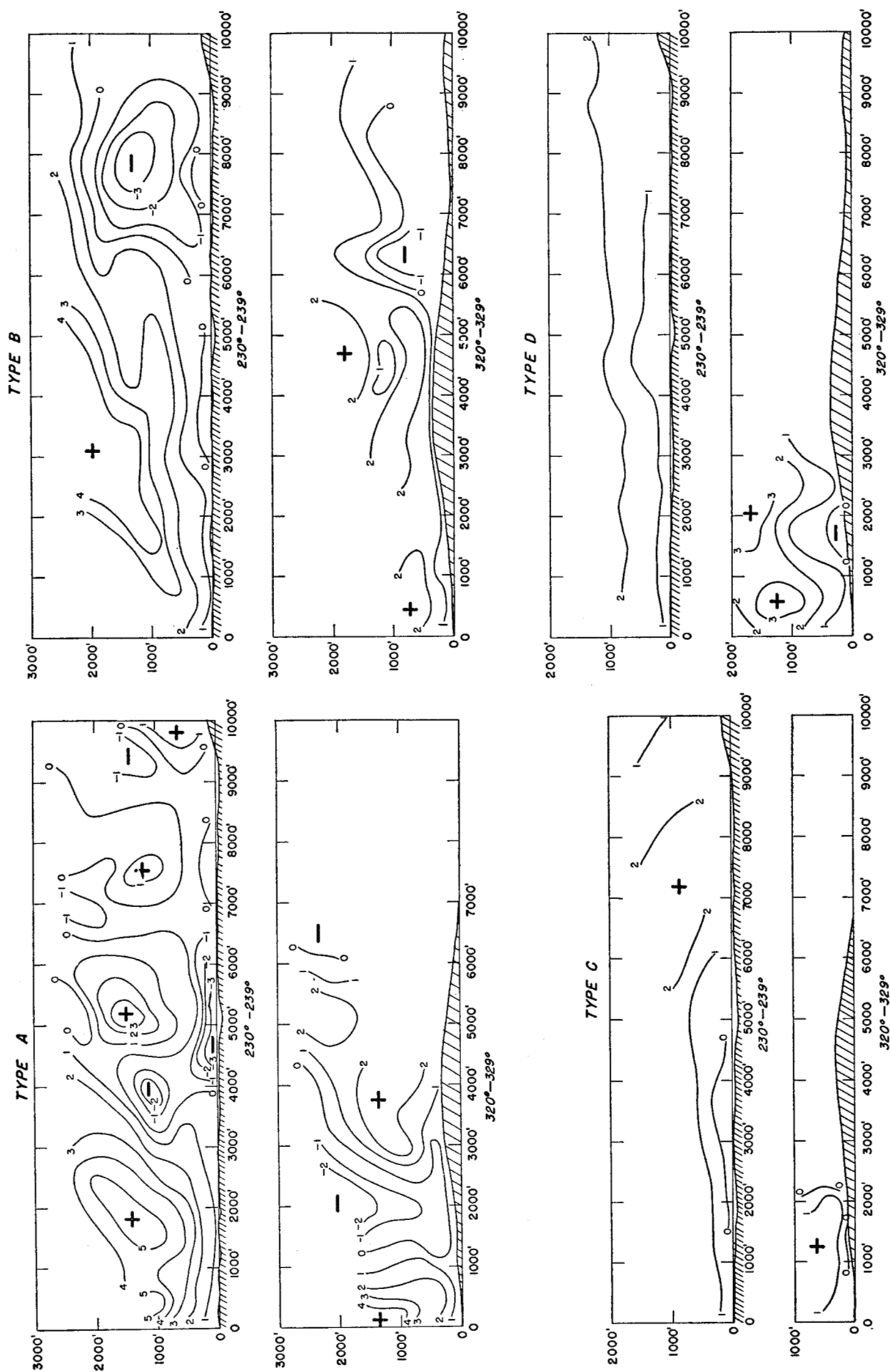


FIGURE 11.—Vertical cross-sections showing the average distribution of observed vertical velocities (m. p. h.) in 10° areas down-valley (230° to 239°) and cross-valley (320° to 329°) from the neutral balloon release point (of fig. 1).

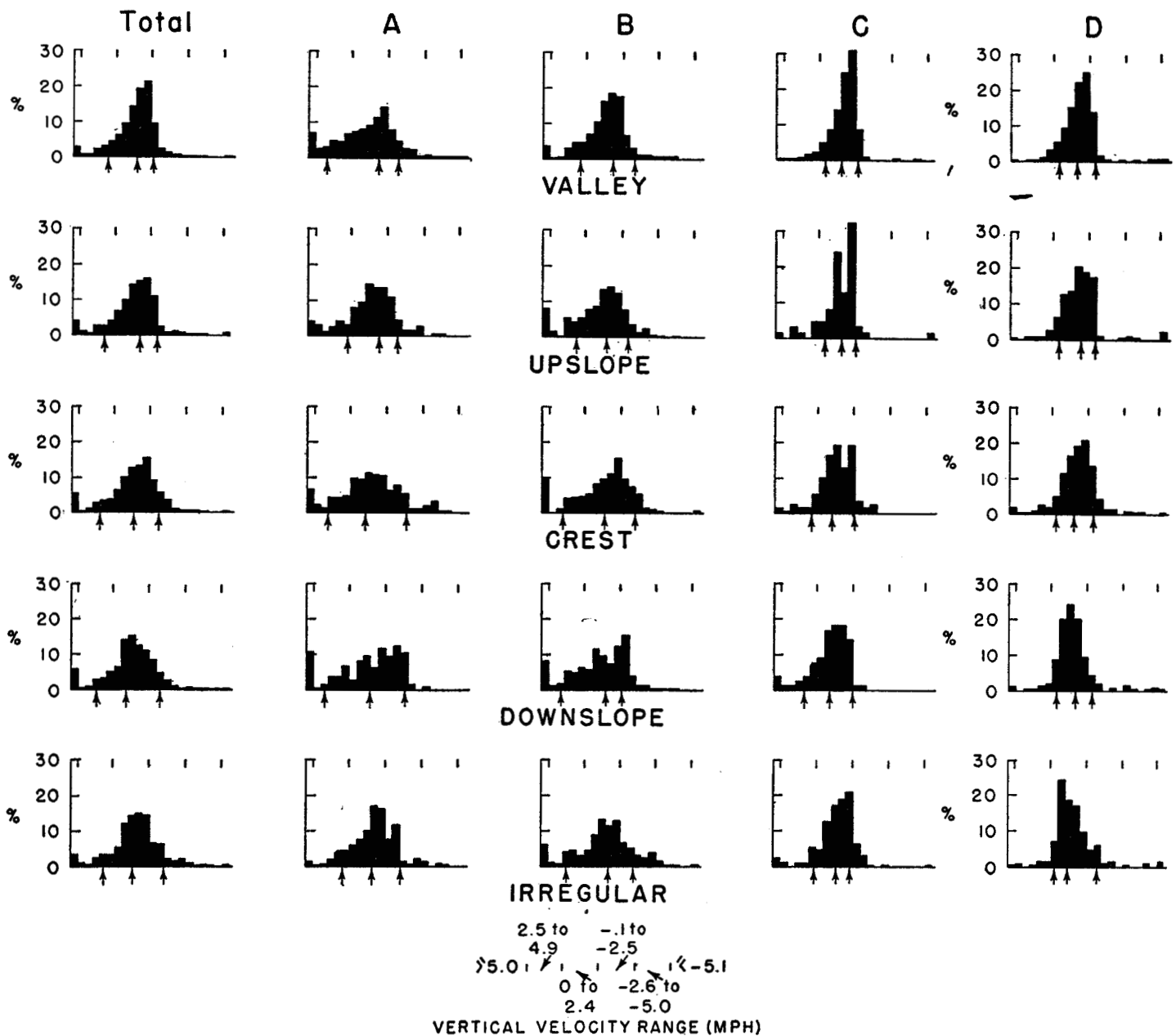


FIGURE 12.—Frequency distributions of vertical velocities over various types of terrain for azimuths from 50° through 229° (south-facing slopes). Arrows mark the  $\pm 12.5$  and the 50th percentile points in each distribution. Note that positive velocities are to the left, negative to the right in this figure, as shown by the vertical velocity range scale at the bottom.

on the average (as we have seen) more probable than downward. The difference between distances from the right- and left-hand arrows to the middle arrow is a rough measure of skewness. The preponderance of positive velocities is attributable, at least in part, to the generally greater probability of getting positive velocities, mentioned earlier. Nevertheless, the effect of left-hand skewness (positive vertical velocities) is quite marked in the upslope and crest types. In fact, one or two of the distributions, particularly the downslope and irregular totals for the south-facing slopes, appear to be skewed the other way. Also, some of the distributions have two modes. The best

examples are the north- and south-facing, downslope, B-types. It is in these distributions that we can most clearly detect the effect of the terrain on the air flow. But notice that, whereas there is a mode well over on the side of negative vertical velocity in the case of the south-facing (heated), downslope B-type, both modes are on the positive side for the corresponding unheated slope. It is tempting, but would not be wise, to try to attribute certain of these modes and skewness to slope winds and others to topographic lifting. More conclusive evidence might be obtained by further stratifying the observations by altitude.

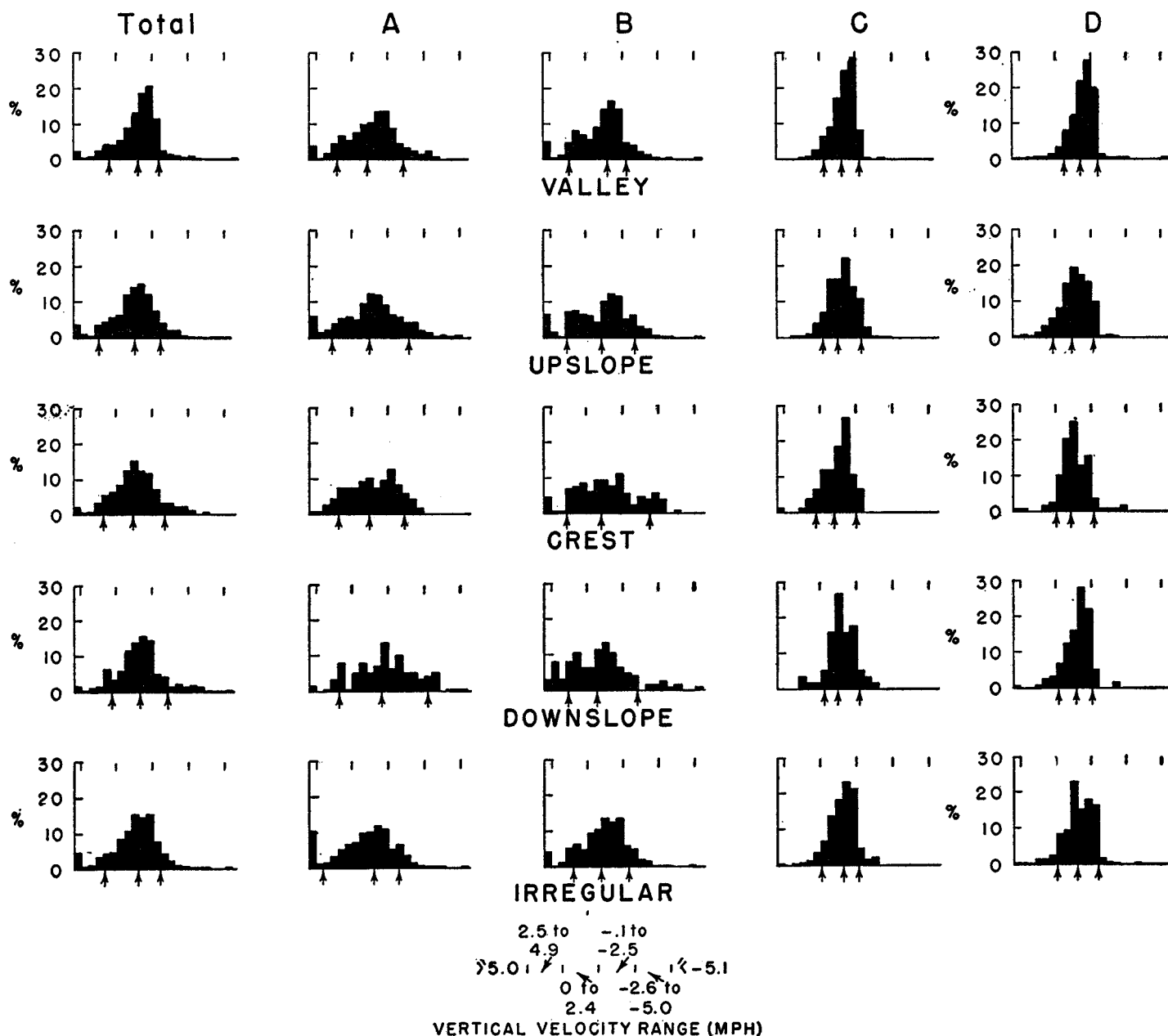


FIGURE 13.—Frequency distribution of vertical velocities over various types of terrain for azimuths from 230° through 49° (north-facing slopes). Arrows mark the  $\pm 12.5$  and the 50th percentile points in each distribution. Note that positive velocities are to the left, negative to the right in this figure, as shown by the vertical velocity range scale at the bottom.

### SUMMARY AND CONCLUSIONS

In this experiment, the paths of air parcels (represented by small, floating balloons) were observed over the hilly terrain near Oak Ridge, Tenn. These were found to fall into four characteristic groups, depending on wind speed and stability conditions. A direct analogy with the four turbulence regimes deduced from the traces of horizontal wind vanes (the Brookhaven turbulence types) was demonstrated, although the balloons necessarily can not be observed in enough detail to reveal very short period fluctuations.

From a number of trajectories, eddy patterns were obtained by subtracting out the mean horizontal velocity vector and plotting the result in  $x-z$  or  $x-y$  coordinates. During unstable conditions (types A and B), these patterns resembled ones found by Lange over much different terrain. No lee eddies were discovered. The conclusion is that the properties of the observed motions do not depend primarily on the large ground obstacles (ridges), but are, rather, characteristic properties of low level air flow; whether thermal or dynamical is not known.

The Lagrangian correlation coefficient between vertical

velocities was computed for eddies of each type in an attempt to determine the time scale of turbulence. The correlation curve failed to tend toward zero in each case from which it was concluded that the duration of the runs was too short to define a time scale.

The mean vertical velocity at various levels was considered, and cross sections of vertical velocity for both the up-valley and cross-ridge directions were constructed. Centers of positive and negative vertical velocity, particularly for types A and B, appeared in these. It was inferred, since means of vertical velocities are involved, that the centers of vertical velocity are associated with terrain features, but with thermal-dynamical effects (slope winds) rather than with a purely topographical lifting, inasmuch as the centers appeared on both cross-ridge and up-valley diagrams.

Frequency distributions of vertical velocities over various types of terrain were obtained. Those types associated with thermal stability (types C and D) had distributions much more peaked than did the A and B types, indicating the strong damping effect on vertical motions associated with stable lapse rate of temperature.

#### ACKNOWLEDGMENT

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